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# Spectroscopic eclipse mapping of oEA stars

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**Abstract.** We present results of a first application of a new computer program for modeling spectroscopic line profiles of eclipsing binaries including eclipse mapping. We apply the program to observed spectra of the oEA star RZ Cas. Basic stellar parameters of RZ Cas are derived from an optimization of the model parameters and compared to those derived from the light curves using the Wilson-Devinney code. Results are in a very good agreement. The comparison of the O-C values obtained from the spectra taken in 2001 and in 2006 support the assumption that a transient phase of rapid mass-transfer occurred in RZ Cas near to the year 2001.

## 1. Introduction

Most of the orbital and global stellar parameters of eclipsing binaries (EBs) can be derived from the light curve analysis by modern programs like the Wilson-Devinney (WD) code [1] that uses physical models of the stars to derive these values. There is a lack of spectroscopic content, however. Extended time series of high-resolution spectra can improve the photometric results and can give additional information e.g. on the orientation of the rotation axes of the EB components. We want to establish a computer program that is able to derive a spectroscopic solution that gives results comparable to the WD solution. The program will be based on modern atmosphere models and line synthesis codes and will compute composite line profiles from both EB components in disk integrated light in all phases of orbital motion including eclipse mapping. In case of Algol-type stars the physics of accretion disks and streaming gas flows has additionally to be taken into account which will be supported by 3D hydrodynamic simulations. Here we present first results from the very first step in establishing the program.

## 2. The program in its actual state

We implemented the calculation of surface intensity and radial velocity distributions, the computation of local line profiles that are shifted according to stellar rotation and position in the binary orbit, and the integration of the line profiles over the visible stellar disks including eclipse mapping. In this first step we assume spherical star configurations and a very simplified treatment of stellar spectral lines. Intrinsic line profiles are composed of multiple Gaussian and Cauchy profiles (see Section 4) to fit the synthetic profiles computed by the SynthV code [2] from atmosphere models calculated with LLmodels [3]. The computation results in a 2D distribution of time series of calculated composite profiles folded with the orbital period. Parameters are optimized by minimizing the O-C values obtained from a comparison with the time series of observed spectra. Table 1 lists the free parameters of the model.

**Table 1.** Free parameters of the actual model. Indices refer to the massive primary and Roche-lobe filling secondary components.

| line shape parameters                              |                    |
|--|--------------------|
| intrinsic central line depths and line widths      | $C_{1,2}, W_{1,2}$ |
| projected rotational velocity                      | $v \sin i_{1,2}$   |
| linear limb darkening coefficients                 | $X_{1,2}$          |
| system parameters                                  |                    |
| RV half-amplitudes                                 | $K_{1,2}$          |
| position angles of the rotation axes               | $\phi_{1,2}$       |
| ratio of total fluxes and stellar radii            | $L_2/L_1, R_2/R_1$ |
| semi-major axis (primary orbit in units of $R_1$ ) | $a_1/R_1$          |
| orbital inclination                                | $j$                |

**Table 2.** Number of RZ Cas spectra, mean SN, mean number of spectra per phase bin, and calculated orbital period for the two data sets.

| epoch | $N_{\text{spec}}$ | $SN$ | $N_{\text{bin}}$ | $P_{\text{orb}}$ | phase gaps |
|-------|-------------------|------|------------------|------------------|------------|
| 2001  | 951               | 200  | 6                | 1.1952410 d      | yes        |
| 2006  | 498               | 85   | 4                | 1.1952595 d      | no         |

### 3. The oEA star RZ Cas

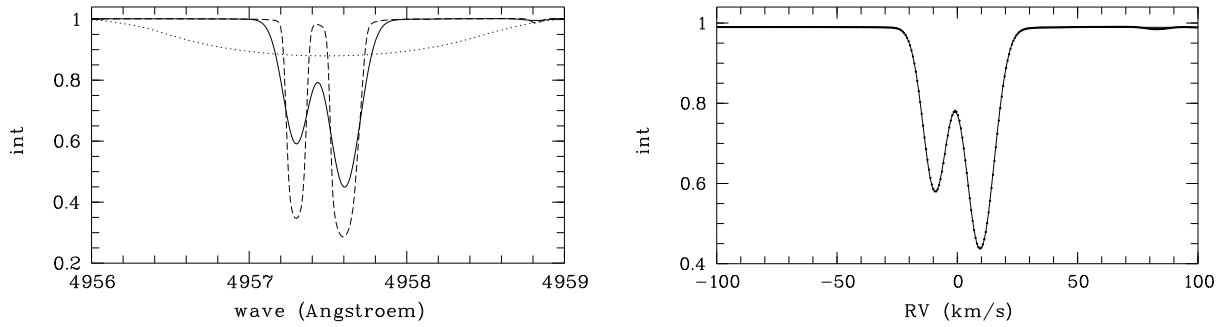
The oEA (oscillating EA) stars are a recently established group of pulsating variables [4]. The members of this group are Algol-type systems that show mass-accretion and oscillations of the primary (gainer). Because of the occurrence of phases of rapid mass-transfer they allow for a direct study of the interaction between stellar evolution and pulsation properties.

RZ Cas is the best investigated oEA star and the only member of this group where extended spectroscopic observations exist. It is an eclipsing semi-detached active Algol-type system with A3 V primary and K0 IV secondary components. Photometric [5] and spectroscopic [6] investigations showed that the pulsations of the primary changed from apparently mono-periodic to multi-periodic behavior. Over the years we observed changes of the amplitudes of the pulsation modes and of the frequency patterns as well as different strength and asymmetry of the Rossiter-McLaughlin effect (RME). The amplitudes of the pulsation modes are modulated with the position in the binary orbit [6], this modulation changes with time as well [7]. The observed secular changes, including the observed instabilities in the orbital period, are thought to be initiated by transient phases of rapid mass-transfer.

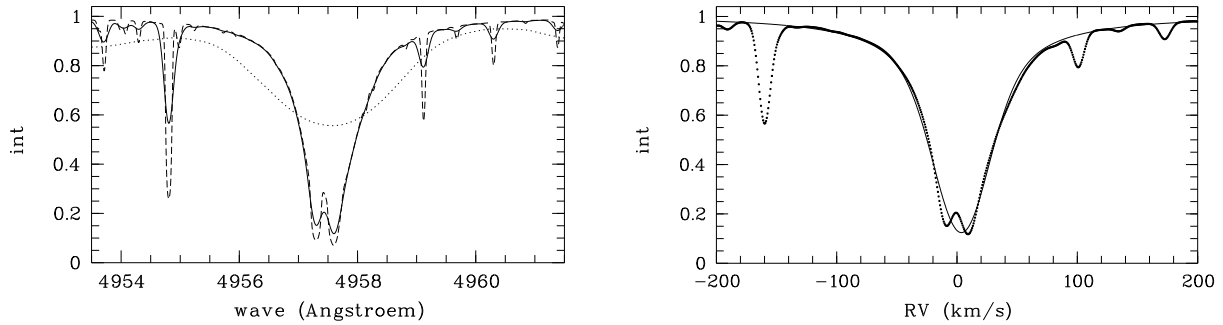
### 4. Application to RZ Cas

Table 2 gives an overview about the two extended data sets of time series of high-resolution spectra of RZ Cas obtained with the Coude-Echelle spectrograph at the 2-m telescope at the Thüringer Landessternwarte in 2001 and in 2006. The listed orbital periods were derived for both data sets separately, from the radial velocities (RVs) measured by a cross-correlation over the wavelength range from 4915 to 5670 Å.

We used these spectra for a first test of the program, despite of the fact that the program



**Figure 1.** The FeI 4957 Å doublet calculated for the primary of RZ Cas with  $T_{\text{eff}}=8550$  K. Left: Intrinsic profiles (dashed), broadened by the apparatus profile (solid), and broadened by  $v \sin i = 75$  km/s (dotted). Right: Profiles rebinned to RV scale and broadened by the apparatus profile (dots) and fitted by multiple Gaussian and Cauchy profiles (solid).



**Figure 2.** As Figure 1 but calculated for the secondary with  $T_{\text{eff}}=5000$  K.

**Table 3.** Parameters taken from the WD solution [8].  $F$  is the rotation to orbit synchronization ratio.

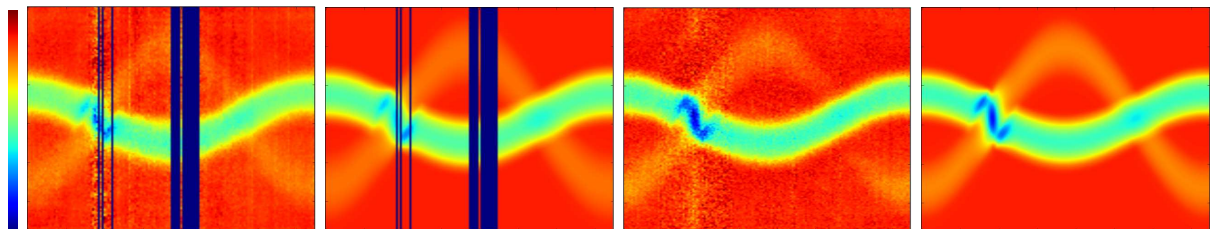
| parameter           | primary | secondary | parameter           | primary | secondary |
|---------------------|---------|-----------|---------------------|---------|-----------|
| $M$ [ $M_{\odot}$ ] | 2.054   | 0.706     | $L$ [ $L_{\odot}$ ] | 12.15   | 1.48      |
| $R$ [ $R_{\odot}$ ] | 1.593   | 1.931     | $X$                 | 0.661   | 0.646     |
| $\log g$            | 4.347   | 3.716     | $F$                 | 1.22    | 1.00      |
| $T$ [K]             | 8550    | 4590      |                     |         |           |
| $a$                 | 6.641   |           | $j$ [ $^{\circ}$ ]  | 82.622  |           |

code in its actual state is not able to reflect the non-spherical shape of the Roche lobe filling secondary and to count for the inhomogeneous circumstellar environment (accretion annulus, gas flows). Results will show, however, that these non-considered effects are well seen in the residuals of our solution and can be studied there in an extracted form.

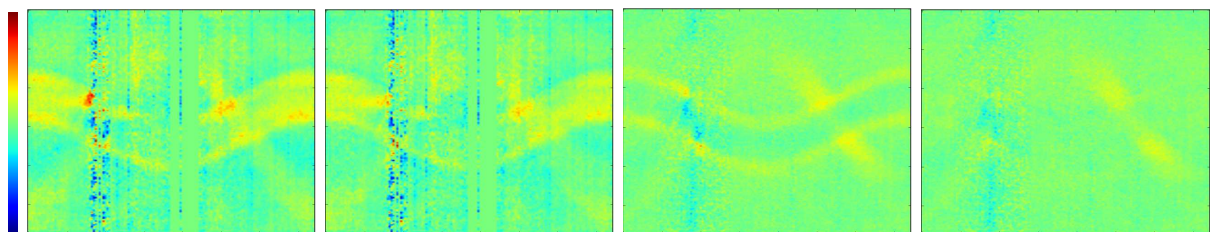
For our analysis we used the Fe I 4957 Å doublet which is sufficiently strong and most unblended. Line profiles have been approximated by multiple Gaussian and Cauchy profiles of free line depths and widths (Figures 1 and 2). Starting values for our model were calculated from the WD solution (Table 3) as obtained in [8]. Time series of Fe I 4957 Å line profiles were rebinned into 100 orbital phase bins by averaging all profiles falling into the same phase bin. First we optimized only the intrinsic line parameters to fit the spectroscopic observations. Then we adjusted all our model parameters iteratively until the line profile intensity O-C values reached

**Table 4.** Comparison of the parameters (see Table 1) derived from the WD solution and from the optimized spectroscopic solution.  $S$  gives the reduction of the sum of squares of the residuals.

| parameter                      |                   | 2006–WD |       | 2006–opt |      | 2001–WD |       | 2001–opt |      |
|--------------------------------|-------------------|---------|-------|----------|------|---------|-------|----------|------|
|                                |                   | prim    | sec   | prim     | sec  | prim    | sec   | prim     | sec  |
| from<br>separate<br>components | $X$               | 0.661   | 0.636 | 0.59     | 0.60 | 0.661   | 0.636 | 0.62     | 0.66 |
|                                | $v \sin i$ [km/s] | 82      | 82    | 71       | 83   | 82      | 82    | 78       | 100  |
|                                | $K$ [km/s]        | 71      | 207   | 71       | 206  | 71      | 207   | 71.5     | 198  |
|                                | $\phi$ [°]        | –       | –     | 90.0     | 90   | –       | –     | 83.1     | 90   |
| global                         | $j$ [°]           | 82.622  |       | 83.1     |      | 82.622  |       | 80.1     |      |
|                                | $a_1/R_1$         | 1.067   |       | 1.067    |      | 1.067   |       | 1.068    |      |
|                                | $R_2/R_1$         | 1.212   |       | 1.215    |      | 1.212   |       | 1.217    |      |
| $S$ [%]                        |                   | 0.47    |       | 0.23     |      | 0.40    |       | 0.32     |      |



**Figure 3.** Observed and calculated time series of Fe I 4957 Å profiles for the data from 2001 and 2006 folded with the orbital period. The horizontal axis spans -0.25 to +0.75 in orbital phase, the vertical axis spans  $\pm 350$  km/s. From left to right: 2001<sub>obs</sub>, 2001<sub>calc</sub>, 2006<sub>obs</sub>, 2006<sub>calc</sub>.

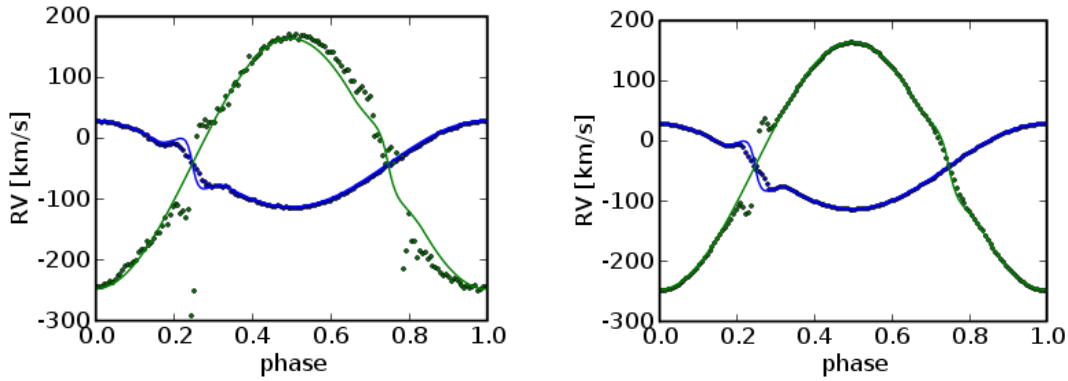


**Figure 4.** O-C values for the solutions based on the parameters taken from the WD solution and on the optimized parameters. The intensity (colour) scale is the same as in Figure 3. From left to right: 2001<sub>WD</sub>, 2001<sub>opt</sub>, 2006<sub>WD</sub>, 2006<sub>opt</sub>.

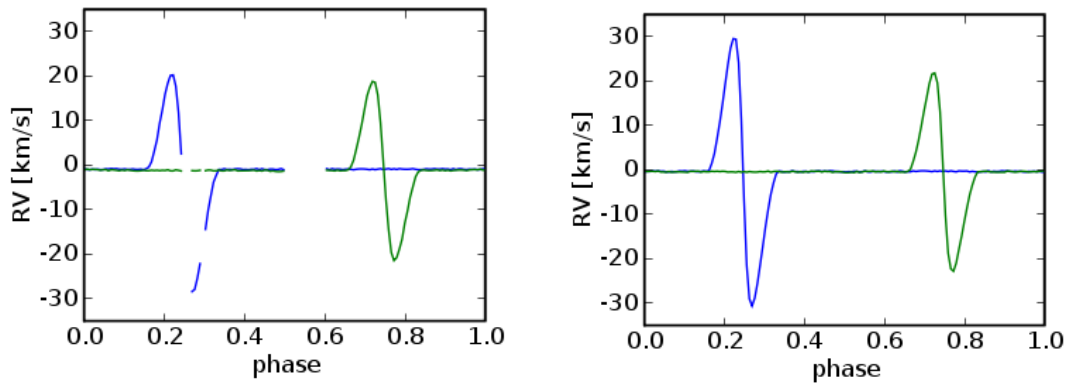
minimum. The luminosity ratio of the components was fixed according to the photometric values (Table 3).

## 5. Results

Table 4 lists the finally obtained parameters in comparison with those calculated from the WD solution. Figure 3 compares the observed and calculated time series of line profiles and Figure 4 shows the corresponding 2D O-C distributions. For the data from 2006 one can see, from the last panel in Figure 4, that except for a larger region around secondary minimum almost all residual intensity structures in the O-C values have been removed by the spectroscopic solution.



**Figure 5.** RVs of RZ Cas in 2006 measured by multiple Gaussian fits from the observed composite line profiles (left) and from the calculated composite profiles (right) for the primary (blue) and the secondary (green). "Real" RVs measured from the first moments of the calculated separate profiles are shown by solid curves.



**Figure 6.** The Rossiter-McLaughlin effect in 2001 (left) and in 2006 (right) during primary (blue) and secondary (green) minima shown by the difference between the RVs calculated from the first order moments of the separate profiles and the RVs taken from the orbital solution.

Remaining features come from unresolved blends and the different SN due to different numbers of co-added spectra per phase bin. The bright feature at secondary minimum is assumed to be produced by the attenuation effects by the dense gas around the primary.

Comparing the parameters derived for the data from 2006 with those of the WD solution we see that there is only one obvious difference that gives rise to the better goodness of our fit, namely the difference in the  $v \sin i$  of the primary that is overestimated in the WD solution; the assumed synchronization ratio of  $F = 1.22$  seems to be too large. Results for the 2001 data are more complex due to the much more structured circumbinary gas distribution and its attenuation effects.

We measured the RVs from the observed and from the calculated composite line profiles using multiple Gaussian fits as well as from the computed separate profiles using the first order moments. Figure 5 shows the results. Compared to the RVs derived from the computed separate profiles, the multiple Gaussian fits introduce large deviations at both eclipses for the secondary component whereas the amplitude of the RME at primary eclipse is underestimated. Figure 6 was calculated from the first order moments of the separated line profiles. It shows that in 2001 the RME was less pronounced but more anomalous (asymmetric) compared to 2006.

## 6. Conclusions

Results show that it is possible to reproduce the photometrically obtained parameters with our spectroscopic solution within a good agreement. This was achieved despite our simple assumptions on the intrinsic line profiles and neglecting basic phenomena in Algol-type systems like the non-spherical geometry of the Roche lobe filling secondary and the influence of the inhomogeneously distributed circumbinary matter. Due to the latter facts WD gives for most of the derived parameters the more accurate values. Typical spectroscopic parameters like the projected rotation velocity (synchronization factor  $F$  in WD) or the RV semi-amplitudes (mass ratio in WD) are better constraint by the spectroscopic solution even in its actual, simple form, however. Only the spectroscopic solution allows for a determination of the position angles of the rotation axes of both components in the observers plane. The different position angles obtained here reflect the different asymmetric attenuation of the photospheric light through circumbinary density gradients and not really different inclinations, however.

In 2006 we find in the line intensity O-C values only a large feature around Min. II that can be interpreted as the attenuation effect of the accretion annulus around the primary. From the spectra obtained in 2001 we observe more complex structures in the 2D O-C distribution due to a more complex and inhomogeneous circumbinary gas distribution that also weakens the RME during primary eclipse and distorts its symmetry. These observations support the assumption that a transient phase of rapid mass transfer took place in 2000-2001 as the star changed its orbital period and its pulsation from apparently mono-periodic to multi-periodic [8].

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